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Workpiece setup simulation based on machinable space of five-axis machining centers

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Abstract

An actual machining center specification, e.g. the axes travel, the workpiece size allowance, etc., needs to be considered for constructing a machining process plan. In this paper, a machinable space of a five-axis machining center is proposed for simulating the workpiece setup. The machinable space is constructed by a table region and a tool cone. The tool cone is an allowance of the spindle diameter and the cutting tool length. By fitting in the visibility area from a total removal volume (TRV) of the machining process plan, a TRV network can be established. The workpiece setup is estimated by positioning the TRV network within the table region. The positioning process can be used for estimating the number of setup changes on the corresponding machinable space.

Keywords: machinable space; workpiece setup; five-axis machining; process planning

1. Introduction

Manufacturability analysis is considered to be essential in reducing the planning time of a machining process plan. One important factor of manufacturability is the workpiece setup planning. Current machine tools have the capability of performing a five-axis machining process [1, 2]. The time required to define the workpiece setup increases because more axes have to be considered than in the three-axis machine tool. The conventional way to define this setup mostly depends on the skills of experts. As a complementary procedure, several fixtures have been invented for reducing the complexity of the workpiece setup in the five-axis machining center. However, fixture planning also requires a large amount of time and labor. The dependencies on the skills of experts and the fixturing process need to be reduced to simplify the workpiece setup.

Previous studies have investigated several methods for efficiently orienting the workpiece. The workpiece orientation is considerably useful for defining any related successive processes, e.g. the setup planning, the fixture planning and the tool path planning. In this study, a new method is proposed for defining the workpiece setup that can align with and support the machining process plan. This paper consists of six sections. In the second section, the previous studies related to setup planning are described. The third section describes the issue of setup planning. The fourth section explains the details of the proposed methodology. The fifth section discusses an example and results. The sixth section states the conclusion and future work.

2. Theoretical background

2.1. Visibility map and the workpiece orientation

The use of a visibility map has been introduced by Woo et al [4] for estimating the cutting tool access requirement of particular workpiece shapes. The visibility map is represented as a visibility cone in Fig. 1. Afterward, Kang and Suh [5] introduced a binary spherical map (BSM) approach as a further enhancement of the visibility map. The BSM is constructed by projecting the visibility cone onto a virtual

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sphere. The smallest travel distance of the cutting tool can be achieved by finding the intersection of any feasible tool motion with the BSM. Lee et al [6] proposed an evaluation methodology, called the Preliminary Manufacturability Evaluation System (PMES), which incorporates the visibility cone into a workspace analysis. PMES can find the optimal workpiece orientation and configuration on the machine tool. Moreover, Anotaipaiboon et al [7] introduced a similar method to the visibility cone by considering a set of the cutting tool contact points and the cutting tool orientation. To define the workpiece orientation, a least-squares optimization procedure is executed for finding the minimum kinematics error during axes rotation.

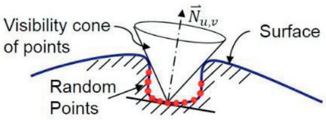

Fig. 1. Visibility cone.

2.2. Machinable space

Apart from the previously mentioned studies, Nishiyama et al [8] introduced a machinable space for positioning the workpiece. The machinable space is used for exposing the actual machining space that can be used for machining. The machinable space, with a maximum 420 mm X travel, 210 mm Y travel and 400 mm Z travel, is shown in Fig. 2. Figure 2 shows a condition in which the mounting table is tilted to its maximum B-axis rotation (until colliding with the spindle). To create the machinable space, several points, as depicted in Fig. 3-a, are calculated using a transformation function in Eq. (1). In Eq. (1), t_{Bx} and t_{Bz} are the offset points of the center of the B-axis centroid in the X- and Z-axes, respectively, which are calculated from the center of the mounting table. The entire machinable space can be constructed by considering several angle rotations, as depicted in Fig. 3-b.

$$\begin{bmatrix} x_W \\ y_W \\ z_W \\ 1 \end{bmatrix} = \begin{bmatrix} cos\theta & 0 & -sin\theta & t_{Bz}sin\theta - t_{Bx}cos\theta + t_{Bx} \\ 0 & 1 & 0 & 0 \\ sin\theta & 0 & cos\theta & -t_{Bz}cos\theta - t_{Bx}sin\theta + t_{Bz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_T \\ y_T \\ z_T \\ 1 \end{bmatrix} \quad (1)$$

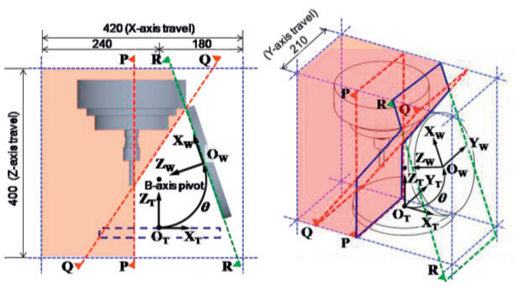

Fig. 2. Example of the machinable space of a maximum table rotation by the B-axis. [8]

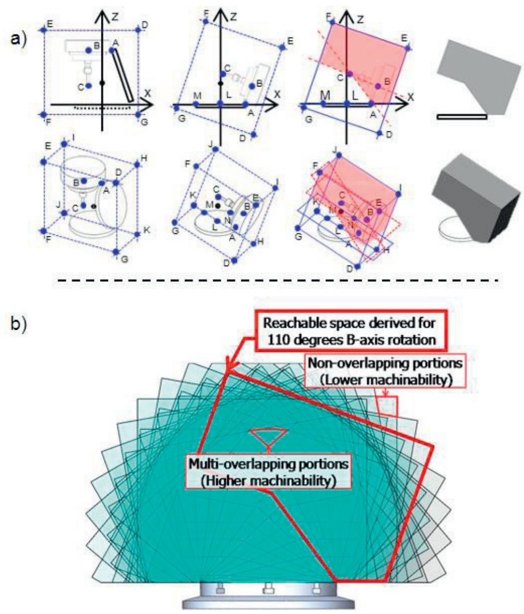

Fig. 3. (a) Determination of machinable space vertices; (b) Total machinable space. [8]

2.3. Total removal volume (TRV) feature-based unit

Generally, the machining process is set to correspond to a particular machining feature. The machining features are calculated from the workpiece shape. For each workpiece model, the machining features are estimated by assuming the initial shape of the material stock is a block or a cylinder. To realize the actual machining condition, this practice has a weakness if any non-standard stock shape is considered in the machining processes. The initial shape and its removal volume can vary, as shown in Fig. 4. To improve the machining feature definition, Isnaini et al [9] proposed a new approach for defining the machining processes based on the shape of the workpiece removal volume. The removal volume estimation is more suitable than using the machining feature definition if the material stock is irregularly shaped. In Fig. 4, the TRV is decomposed into several removal volumes, which in [9] are called TRV features. The TRV features are generated by using reference planes that coincide with each TRV face. The TRV feature corresponds to a particular reference plane. Further, the corresponding reference plane will represent the machining plane.

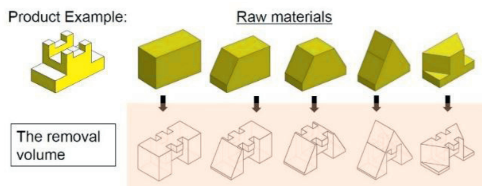

Fig. 4. Workpiece instances, raw materials and the corresponding removal volume.

3. Issues in setup planning

The workpiece setup can be designed in many ways in the five-axis machining center. To be more competent, an actual machining center specification, e.g. the axes travel, the workpiece size allowance, etc., needs to be considered in advance. Nowadays, several kinds of machining center specifications are available. However, it is believed that the actual machining environment has not yet been exploited effectively for planning the workpiece setup. The studies described in the previous section are believed to show optimum results in achieving the best workpiece orientation for the workpiece setup procedure. In general, the initial position of the workpiece is defined by putting the workpiece in the most stable position and aligning its centroid with the center point of the mounting table. So, even though the workpiece is oriented by considering any five-axis motions, the workpiece centroid will never be moved away from its initial position. Consequently, the adjusted workpiece orientation might achieve an unexpected workpiece position that needs further fixture configuration in order to firmly clamp the workpiece. Considering time and cost limitations, the workpiece setup plan with a less complex fixturing process is needed. Moreover, the idea to incorporate the machinable space is considered to be very supportive for determining the actual machining area that can be utilized.

4. Proposed methodology

In this study, a new methodology for planning the workpiece setup is proposed. The methodology is divided into four main steps. In the first step, the machinable space is constructed for confirming the feasible machining area. In the second step, the requirement of the visibility cone for each TRV is calculated. In the third step, the workpiece modeling based on the TRV is presented. In the fourth step, the workpiece orientation is adjusted by positioning each TRV feature according to its visibility cone requirement. Based on the machine tool configuration in [3], a type of [*W/cbxy(C)/T*] five-axis machine tool (as shown in Fig. 5) is used for the machine tool model.

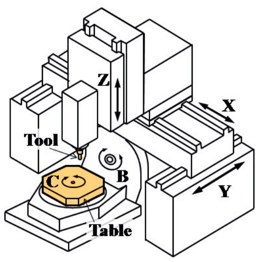

Fig. 5. Example of five-axis machine tool with [*W/cbxy(C)/T*] configuration.

4.1. Tool cone and improved machinable space

In order to construct a model of the actual machining specification, a tool cone and an improved machinable space are used. The tool cone is determined by using the spindle diameter, R_S, and the tool length, t, as depicted in Fig. 6. The opening angle, ϑ is given by Eq. (2), where in most machines, R_S is mostly fixed, but t will correspond to the cutting requirement. The tool cone is assumed as the safest allowance for the cutting tool and the spindle when travelling within the machining space.

$$\vartheta = 2tan^{-1}\left(\frac{R_S}{t}\right) \quad (2)$$

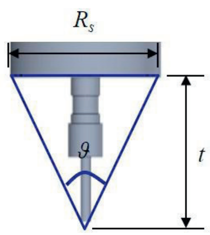

Fig. 6. Tool cone determination.

Using an approach similar to that in [8], the machine tool specification is used for modeling the machining space as depicted in Fig. 7. The machining space is limited to X, Y, and Z maximum travel, which are denoted by R_x, R_y, and R_z, respectively. The mounting table is limited to the diameter, D, and is able to be only rotated by the B- and C-axes.

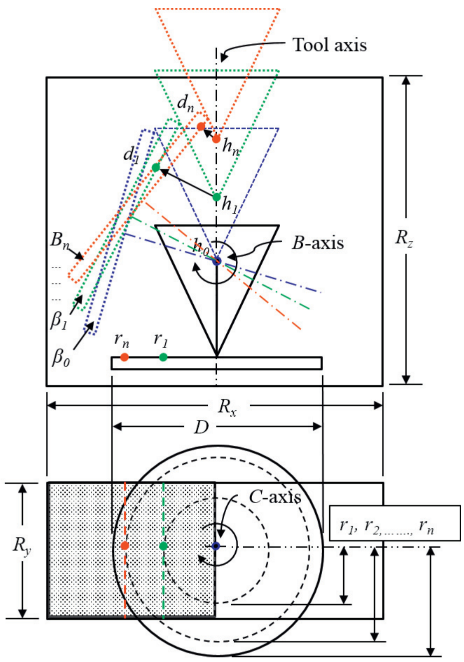

Fig. 7. Table region determination.

To analyze the machinable space, three assumptions are established as follows:

- The cutting tool cone tip is initially aligned with the B- and C-axes.

- The initial condition of the tool cone and the mounting table are defined as the maximum mounting table position for colliding with the tool cone. This condition can be achieved by positioning the tool cone to h_0 and the mounting table to β_0, as depicted in Fig. 7.
- And, the C-axis can be rotated 360°.

Previous assumptions ensure the validity of using only half of the mounting table for modeling the machinable space. In Fig. 7, a clockwise rotation of the mounting table is chosen as an instance. h_0 is the maximum travel of the tool cone to reach the center of the table. The B-axis position can be defined as the offset point $\{t_{Bx}, t_{By}, t_{Bz}\}$ in Eq. (1) according to [8]. Further, β_0 is achieved by aligning h_0 with the B-axis. The next rotation angle, β_n, is given by Eq. (3). To construct the mounting table region as shown in Fig. 7, an angle interpolation, ϐ, is needed.

$$\beta_n = \begin{cases} \beta_0 + ϐ, n = 1 \\ \beta_{n-1} + ϐ, n \geq 2 \end{cases} \quad (3)$$

The mounting table rotation by ϐ will eventually limit the tool cone to reach h_0, and shifts the tool cone upward to a new position, h_n. Two steps are needed for calculating the h_n. In the first step, an imaginary collision point, *CP*, that occurs between the mounting table and the tool cone is calculated by transforming the mounting table edge point, *EP*, using Eq. (1). The next step is to project the *CP* by the Z-axis to the tool cone, which is positioned in h_0. Subsequently, the projection point will be defined as another imaginary intersection point, *CP',* as depicted in Fig. 8. At this state, we can ensure that the $|h_0\text{-}h_n|$ line is parallel and equal with the $|CP\text{-}CP'|$ line. If the angle, α, is defined by $(180 - \beta_n)$, then the $|d_n - p'|$ distance will equal the $|h_n - h_n'|$ distance, in which p' is a rotated point of the center of the table, p, and h_n' is the projected h_n. As depicted in Fig. 8, d_n is the maximum travel for the tool cone if the mounting table is angled by β_n. Thus, the mounting table region, r_n, that corresponds to d_n can be calculated by Eq. (5). The mounting table rotation is repeated until the tool cone tip coincides with the edge of the mounting table, or $CP = h_n$.

$$|h_0 - h_n| \cong |CP - CP'| \quad (4)$$

$$r_n = |d_n - p'| = |h_n - h_n'| \cong |h_0 - h_n| sin(\alpha) \quad (5)$$

4.2. Enhancement of TRV features

To incorporate the TRV, the TRV features need to be prepared with a visibility cone, *VC*, specification. The *VC* can be determined by analyzing critical points on the TRV as depicted in Fig. 9. The critical points are analyzed by aligning the tool cone and adjusting the tool cone size. The tool cone is aligned for ensuring that the tool cone tip can reach the critical point. There are two kinds of alignment: clockwise, $\overrightarrow{TC}_{cw}$, and counter-clockwise, $\overrightarrow{TC}_{ccw}$. Please note that in Fig. 9, the tool cone is being aligned instead of the mounting table in accessing the critical points. The clockwise rotation is considered as the B-axis positive direction.

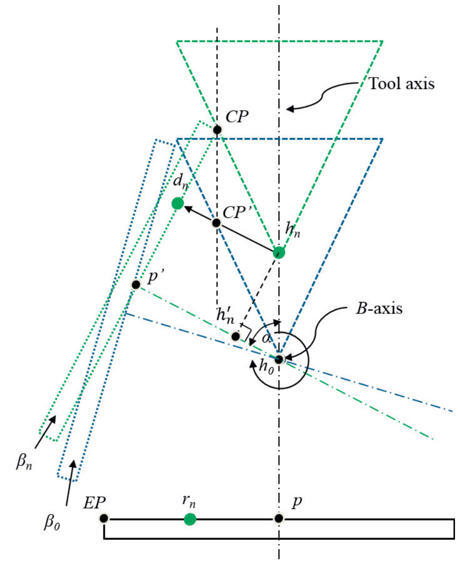

Fig. 8. Mathematical operation.

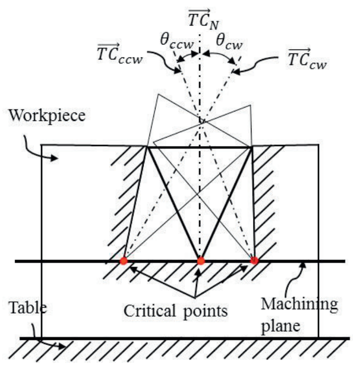

Fig. 9. Visibility cone in TRV.

In accordance with this, the tool cone size needs to be adjusted by using a different tool length to maintain the accessibility of the tool cone. For instance, in Fig. 10, three types of tool length, *t,* are needed: t_N, t_{cw}, and t_{ccw}. To minimize the number of tools required for the corresponding TRV, a suitable tool length, t^*, is selected by using Eq. (6).

$$t^* = max(t_N, t_{cw}, t_{ccw}) \quad (6)$$

Afterward, *VC* is defined by Eq. (7). θ_{cw} and θ_{ccw} are the alignment of the tool cone for clockwise and counter-clockwise adjustment, respectively, as depicted in Fig. 9. Moreover, θ_{add} is an adjustment of the TRV machining plane if it is in an inclined position, as depicted in Fig. 11. If the normal of the TRV machining plane is parallel with the cutting tool axis (Z-axis), then θ_{add} is 0. Each TRV feature has its own *VC* specification.

$$(|\theta_{add}| + \theta_{cw}) \leq VC \leq (|\theta_{add}| - \theta_{ccw}) \quad (7)$$

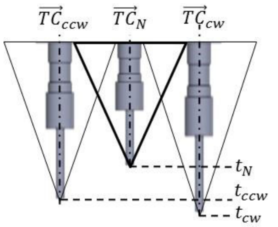

Fig. 10. Variety of tool cone sizes based on tool length.

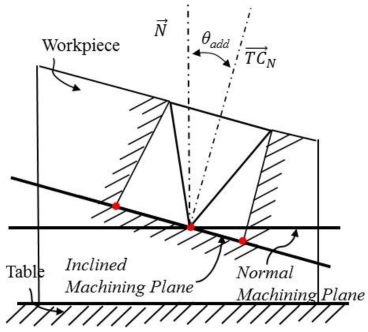

Fig. 11. Inclined TRV machining plane.

4.3. Workpiece setup requirement based on TRV

In this study, the TRV features are used for modeling the requirement of the workpiece setup. Each TRV feature represents the removal volume shape. There are two main aspects of the TRV that can be inferred from [9]. First, the TRV features are defined as a convex shape. This definition ensures the centroid of each TRV is inside the removal volume. Second, a virtual sphere centroid is used as the reference for each TRV feature. From this point forward, the virtual sphere centroid will be called the "network center". Thus, the workpiece can be represented as a TRV network, as depicted in Fig. 12. The TRV network shows the relative position between the network center and the TRV feature's centroids. The TRV network is used to roughly estimate the position and alignment of the workpiece model, and it can be expressed by Eq. (8). The TRV feature's centroid is denoted by TRV_n. The n value indicates the importance of the TRV feature among all TRV features.

$$PM \equiv \{TRV_1, TRV_2, \dots, TRV_n\} \tag{8}$$

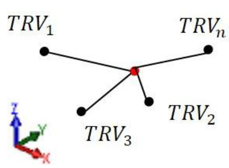

Fig. 12. TRV network.

4.4. Workpiece positioning method

The last step of the methodology is the procedure to position the workpiece into the advised location on the mounting table. The *VC* specification of the TRV feature is used for positioning the TRV network into the correct mounting table region. Initially, the network center is aligned with the center of the table, as depicted in Fig. 13. Each location difference, ε_n, between the TRV_n and the required region, r_n^*, on the mounting table is calculated by Eq. (9). The closest point on r_n^* from TRV_n is defined as ap_n. Further, several translations and rotations of TRV_n are needed until the entire TRV_n can be put inside its r_n^*. Each translation or rotation is based on TRV_n that has a positive value of ε_n, which is denoted by TRV_n^*. After all TRV_n^* are calculated, the TRV with the lowest n will have the first priority to be put in its r_n^*. Please note that each translation or rotation by TRV_n^* affects the entire TRV_n position. Moreover, the entire TRV_n must be still inside the table diameter, D.

$$\varepsilon_n = \begin{cases} -1 \times |\overrightarrow{TRV}_n - \overrightarrow{ap}_n|, & if\ (\overrightarrow{TRV}_n - \overrightarrow{ap}_n)\ leads\ inward \\ |\overrightarrow{TRV}_n - \overrightarrow{ap}_n|, & if\ (\overrightarrow{TRV}_n - \overrightarrow{ap}_n)\ leads\ outward \end{cases} \tag{9}$$

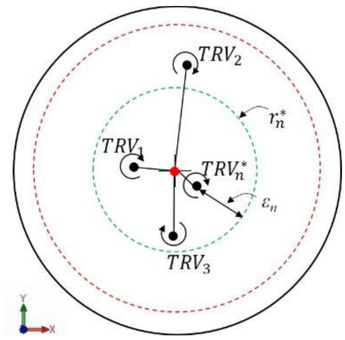

Fig. 13. Positioning procedure illustration.

As shown in Fig. 13, the positioning procedure is taken only on the X-Y axis. This is because, to achieve a less complex fixturing setup, the positioning process on the X-Z or Y-Z axis is not necessary. However, it is believed that the proposed procedure may result in an un-feasible solution after several rotations and translations by TRV_n^*. Therefore, a simple objective needs to be defined, such as to minimize all ε_n. Moreover, the combination of sequences between rotation and translation can be pre-configured to achieve the best configuration.

Furthermore, if the positioning procedure limit is achieved and there are still TRV_n^* that are not in its r_n^*, the positioning procedure is replicated again by selecting the remainder TRV_n^* with the lowest n. Based on the selected TRV_n^*, select any random point within its r_n^* and define this as the new initial position of the TRV network. Then, restart the positioning procedure for the remainder TRV_n^*. This additional positioning procedure will be counted as a different workpiece setup. Fewer additional positioning procedures will reduce the number of workpiece setups.

5. Example

An example of the TRV network on an imaginary TRV is depicted in Fig. 14. The area with a darker color shows the workpiece and the lighter color shows the TRV. The proposed methods are used to generate the TRV network based on the available TRV. By using Eq. (8), the TRV network can be expressed as $PM \equiv \{TRV_1, TRV_2, TRV_3, TRV_4\}$. Each TRV_n is known to have a specific *VC* specification. The initial tool access direction (TAD) from each TRV_n is used as the initial orientation. Figure 14 shows that only TRV_2 has the TAD toward the –*Y*-axis direction. In this example, the tool cone is set by t = 20 mm and R_s = 20 mm. Further, the suitable tool length, t^*, is assumed to be 20 mm for all TRV_n. Figure 15 depicts the initial and predicted positions of the TRV network. As illustrated in Fig. 15, the workpiece needs to be placed approximately ε_2 away from the center of the table in order to put TRV_2^* into r_1^*. Since there are no more reminder TRV_n^* in the TRV network, this position is set as the new workpiece orientation. Based on this result, the workpiece will have a single setup procedure to perform the machining process for all TRV_n.

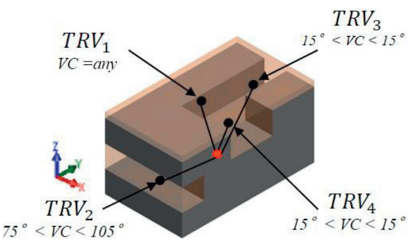

Fig. 14. TRV network on imaginary TRV.

6. Conclusion and future work

In this study, a new procedure to calculate a workpiece setup is proposed. The workpiece setup considers the machinable space of the machine tool that is constructed using the actual machining center specification. By incorporating the TRV, the workpiece can be modeled as a TRV network. The TRV network simply shows the relative position of TRV features in the workpiece. By using the imaginary shape, the proposed setup procedure is verified and shown to roughly estimate the workpiece setup orientation. However, more samples are needed, especially a real workpiece, to assure the robustness of the proposed positioning procedure.

In this study, the workpiece setup procedure still simplifies the suitable tool selection for each removal volume by using the maximum tool length that is allowable to generate the visibility cone specification. This strict rule of thumb may not be suitable for practical conditions. Therefore, the suitable tool selection procedure will be considered to be more flexible. In order to improve the positioning procedure of the TRV network, a proper optimization method will be considered in the future.

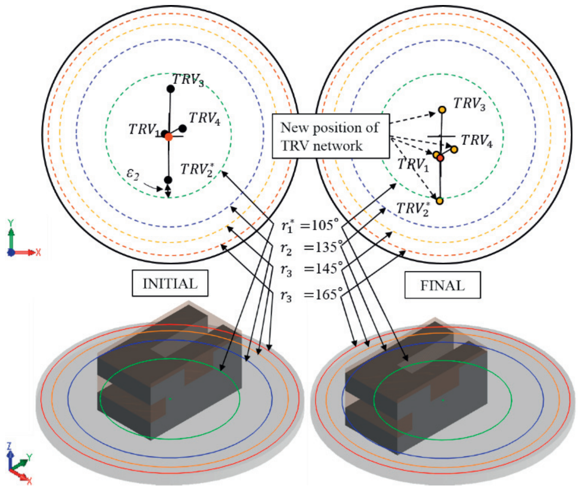

Fig. 15. TRV network positioning: (left) initial; (right) predicted.

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